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Upgrades to the VISAR Streaked Optical Pyrometer (SOP) system on NIF

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ABSTRACT

The Velocity Interferometer System for Any Reflector (VISAR) is a critical diagnostic in Inertial Confinement Fusion and High Energy Density research as it has the ability to track shock fronts or interfaces moving 0.1-100 km/s with great accuracy. At the National Ignition Facility (NIF), the VISAR has recently been used successfully for implosion tuning and equation of state measurements. However, the initial design of the companion Streaked Optical Pyrometer (SOP) to measure spectral radiance - hence shock temperature - suffers from large background levels and poor spatial resolution. We report on an upgrade to improve the spatial resolution in the 560-640nm band by using custom lenses and replacing the Dove prism with a K-mirror and implementing a gating-circuit for the streak camera to reduce background signal. We envision that upgraded SOP will provide high quality data collection matching NIF VISAR's standards.

Keywords: NIF, VISAR, SOP, equation of state, shock wave, streak camera, Dove prism, K-mirror

1. INTRODUCTION

The National Ignition Facility (NIF) is a high energy laser system at Lawrence Livermore National Laboratory (LLNL), principally designed to study Inertial Confinement Fusion (ICF) and High Energy Density (HED) science. The 192 beams of the laser are directed at 1- to 5-mm targets located at the center of the 5-m radius spherical vacuum chamber. Numerous diagnostics are used to verify both beam and target alignment in the target chamber and to quantify the target performance through optical, x-ray and neutron radiation measurements.

Two important diagnostics in dynamic compression experiments are the Velocity Interferometer System for Any Reflector (VISAR) and the Streaked Optical Pyrometer (SOP). These two diagnostics both record 1D images of the target on a streak camera and offer both spatial (in one axis) and time resolved images of the target during compression. Although they share the same collection optics and each has streak cameras located on the same table, they constitute two separate instruments.

VISAR measures the Doppler shift of a probe laser beam using an interferometer to determine the shock or interface velocities (typically ~ 0.1 to >100 km/s).^{1,2} The NIF VISAR has two channels (A and B) both operating in the red at 659.5nm. VISAR is a primary diagnostic for a variety of shock and ramp compression experiments on the NIF to measure equations of state,³ material strength and structure⁴ at extreme conditions and tune the temporal shape of laser pulses for ICF implosions.⁵

The Streaked Optical Pyrometer (SOP) passively measures the time dependence of the spectral radiance between 560 and 640 nm along a 1D image of the target. In equation of state measurements, the spectral radiance is often dominated by thermal emission from dynamically compressed materials in the target. With appropriate calibration, the data can be reduced to provide a measure of the absolute spectral radiance and enables quantitative determination of brightness temperatures.^{6,7}

Due to several engineering challenges specific to implementing such a diagnostic on the NIF, the original version of the SOP suffered from limited performance and did not provide sufficiently high quality data. The goal of this paper is to describe the improvements to this system, which include both increased spatial resolution and decreased streak camera background levels.

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2. MOTIVATION

The original SOP diagnostic has limited performance for multiple reasons. The first was due to the optical design and the second was due to the recording system. The imaging performance was far from diffraction-limited due to the wide bandwidth and collection optics that are not achromatic. The streak camera background levels were high due to the lack of a cathode gating circuit. (See Figure 1.) Both of these performance problems can be addressed by straightforward engineering solutions.

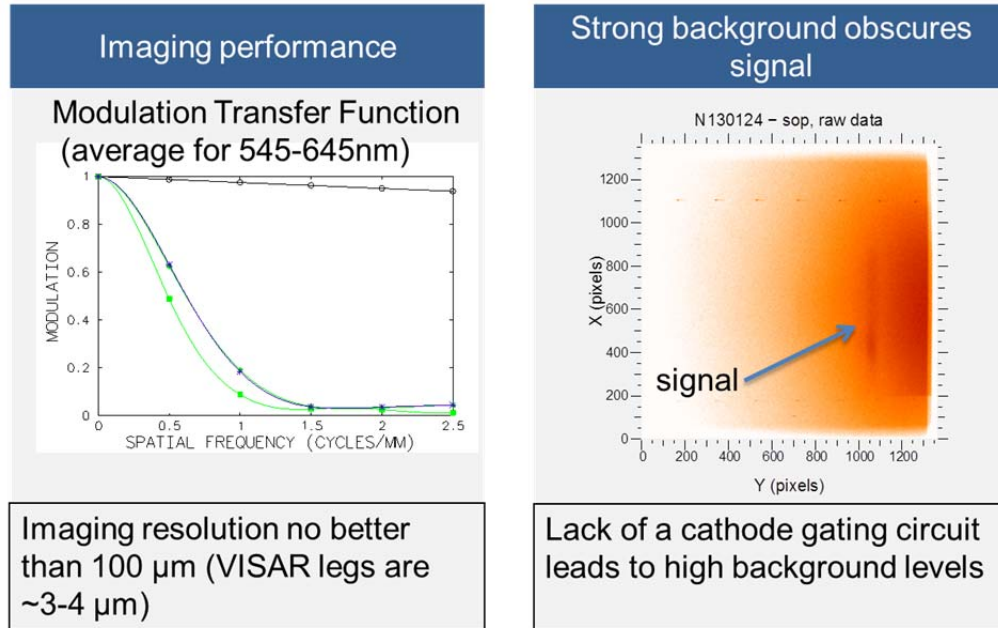


Figure 1: Reasons for upgrading the NIF SOP include poor imaging performance (low MTF) and large streak camera background levels.

Because the original SOP lacked a spatial resolution comparable to its companion VISAR, as shown in Figure 2 it does not act well as complementary system.

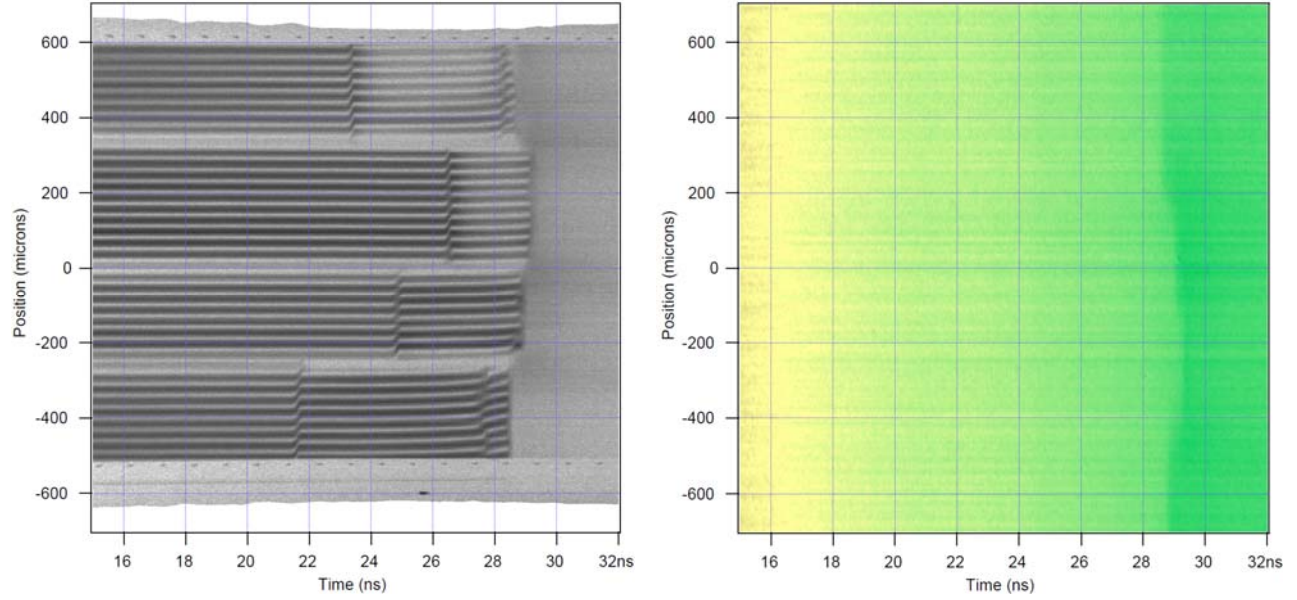


Figure 2: Example data for a ramp compression experiment with a stepped target.³ VISAR data (left) has higher spatial resolution than original SOP data (right) allowing diagnosis of the dynamic compression for each part of the target. In each graph, the vertical axis is the spatial axis and the horizontal axis is the temporal axis relative to T0 (shot time).

3. OPTICAL DESIGN

Overview of VISAR layout

In this section, we briefly review the optical design for VISAR presented in more detail elsewhere.¹ Though VISAR and SOP are separate diagnostics, they share the same collection optics that deliver light to a shared optical table. The f/3 light collection lens (labelled L1 in Figure 3) is inserted into the NIF target chamber (vacuum) on a cart, which rides on rails, known as a Diagnostic Instrument Manipulator (DIM), while all of the other optics and cameras are outside of the target chamber (in air).

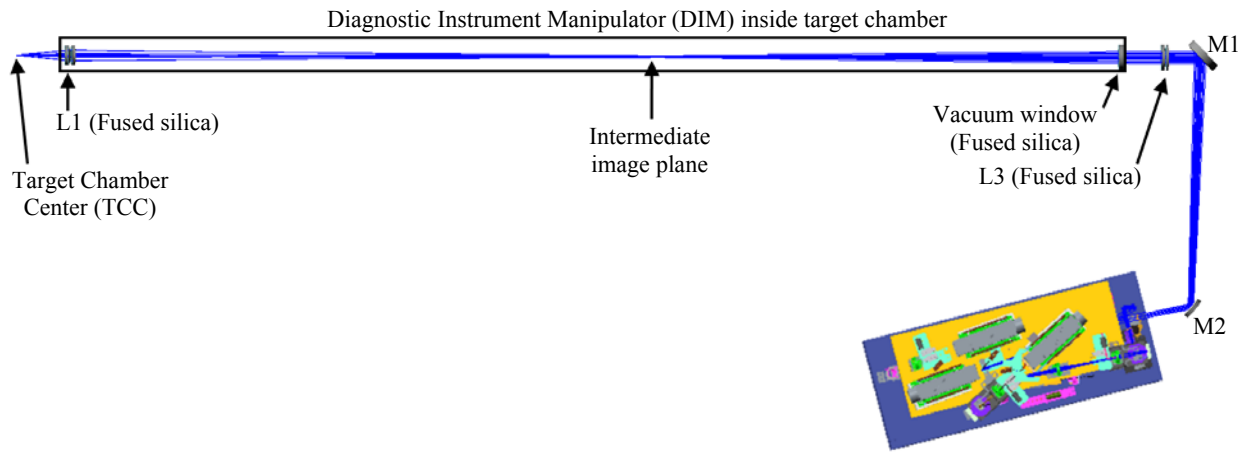


Figure 3: Optical layout for VISAR & SOP. The collection lens L1 is inserted on a cart, which rides on rails into the target chamber, known as a Diagnostic Instrument Manipulator (DIM). For scale, M1 is about 12.8 meters away from Target Chamber Center (TCC).

The light passes out of the target chamber through a fused silica vacuum window and another lens (L3), then is folded onto the two-level VISAR optical table just outside the target chamber by way of two planar mirrors (M1 and M2). A dielectric beamsplitter (BS5) transmits the 659.5nm light to the two VISAR interferometers and reflects the SOP bandwidth (560-640nm) to the SOP leg shown in Figure 4. The interferometers are located on the lower level optical table while the three streak cameras are located on the upper level optical table.

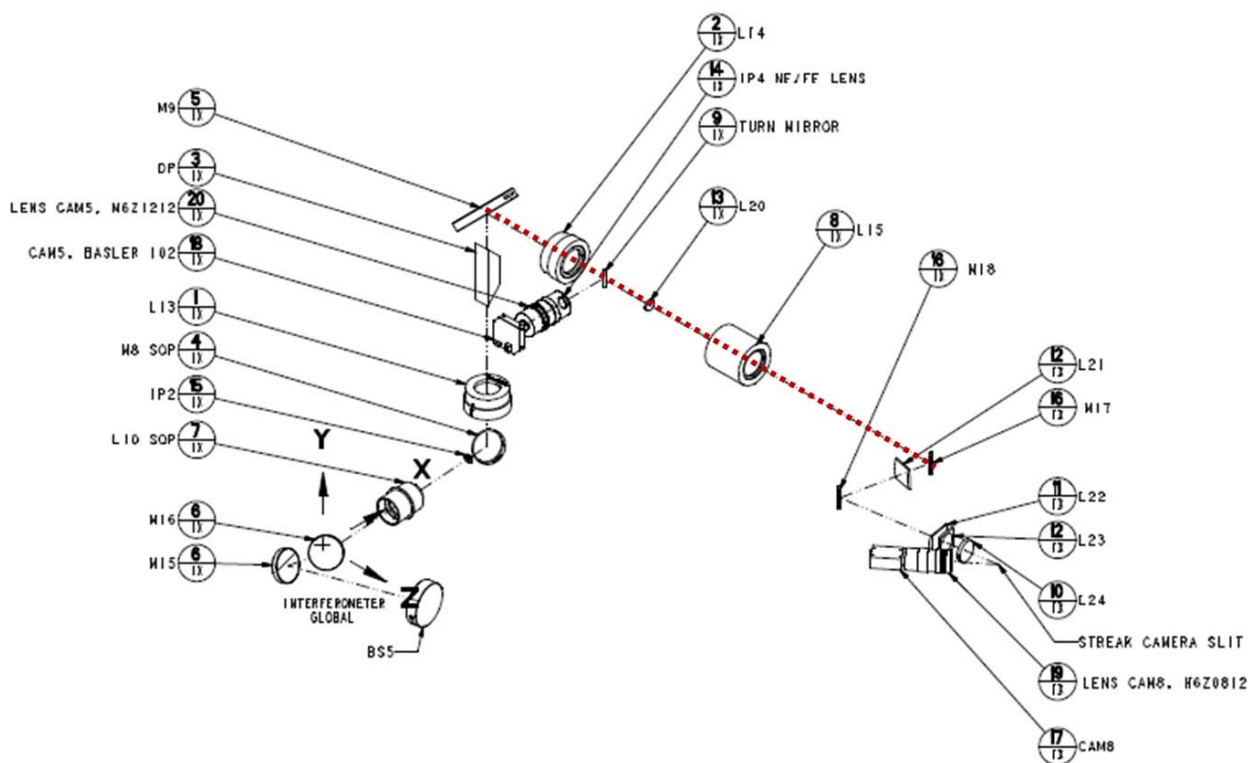


Figure 4: The optical configuration of the SOP leg before the redesign. The redesigned lenses L14 and L15 are located in the space indicated by the dotted line (red online) between M9 and M17. (Cylindrical lenses L20-24 are removed as part of the redesign.)

The main challenge for designing a high quality SOP stems from the use of fused silica collection optics. The lenses L1 and L3, the vacuum window and the beamsplitters are made with fused silica because the transmission through this material is stable when exposed to the radiation emitted by NIF experiments: There are special radiation-resistant glasses, but most glasses exhibit browning when exposed to neutron and gamma rays. Because the fused silica lenses are not achromatic, there is much separation between the intermediate image focal planes when considering the SOP bandwidth 560-640nm. The entire band must be brought into focus at the entrance slit of the streak camera to collect useful images.

SOP optical design improvements

All of the improvements to the SOP optical performance needed to be done without affecting the rest of the VISAR collection optics design. Thus, all of the changes occur after the beamsplitter that separates the light into the SOP leg and need to fit within the same space as before. The optical design changes include replacing a refractive image rotator (a Dove prism) with an all reflective image rotator (a K-mirror), and replacing the final two imaging lenses with custom lenses. Figure 5 shows the new SOP path on the optical table.

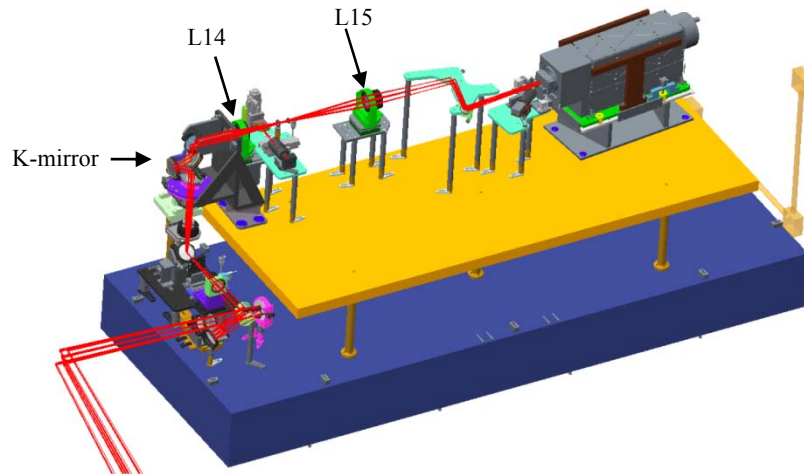


Figure 5: The VISAR/SOP optical table outside the target chamber has two densely-packed levels. For clarity, this view shows only the SOP optics. Lens groups L14 and L15 as well as the K-mirror are part of the redesign. Not showing are the two VISAR interferometers and probe laser delivery optics on the lower level and the two additional streak cameras on the upper level.

Being able to rotate the image at the streak camera slit (a fixed orientation) allows for observation of different line-out directions across the VISAR field of view in the target chamber without rotating the 70-pound streak camera. This is important to be able to support different types of targets. Image rotation can be achieved with reflection off of an odd number of surfaces. A Dove prism was used in the original NIF VISAR design in the path up from the lower optical table to upper table in a nominally collimated space. Unfolded, the Dove prism can be thought of as a thick slab of glass at a tilted angle within the beam: challenging for a high resolution imaging system! Theoretically, a tilted plane parallel plate does not add aberrations to a collimated beam, however any departure from collimation will add aberrations.

A K-mirror is an all-reflective image rotator with three mirrors as shown in Figure 6. Rotating the K-mirror assembly rotates the image by twice the rotation angle, similar to the Dove prism operation.

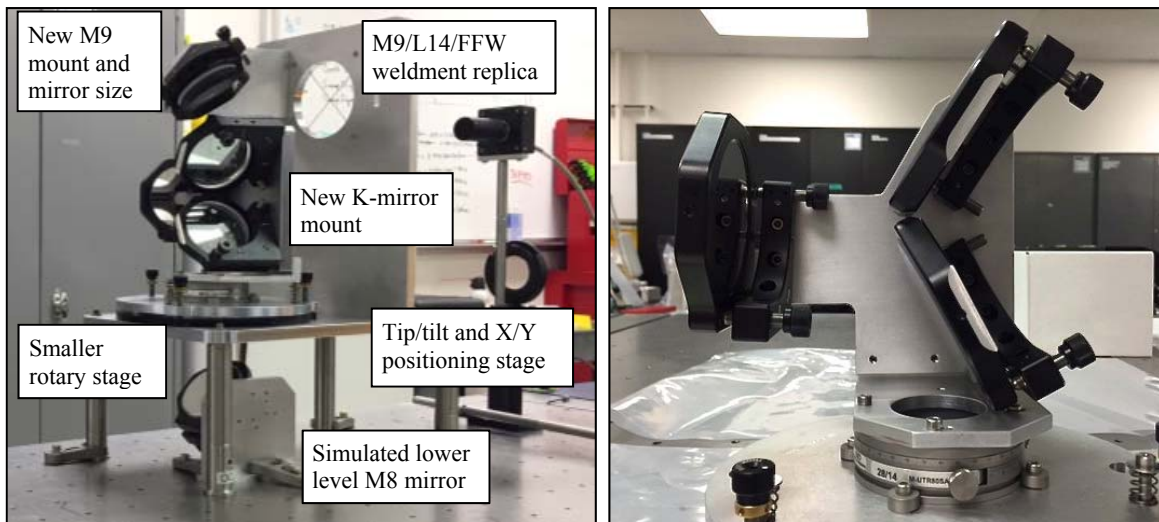


Figure 6: (Left) A K-mirror on a rotation stage. A mirror on the table (M8) reflects light upwards through a hole in a rotation stage to the K-mirror. Light reflects off the three K-mirror surfaces before a mirror (M9) reflects the light through an aperture. Here, shown in this lab test, a camera records the beam stability during rotation. (Right) Close up of K-mirror mount.

The challenge in implementing the K-mirror design in VISAR was that it needed to operate in the same position in the optical layout as the Dove prism previously held and there is only a limited amount of space in this area. Instead of one optical element (a prism) that needed to be installed on the rotation stage, there were now three mirrors, which each needed to be mounted and rotated on a stage.

In addition to reducing the chromatic effect of the Dove prism, a K-mirror is preferred because the additional degrees of freedom allow more precise alignment and can eliminate the wobble in pointing caused by imperfections in the Dove prism fabrication and alignment. In prototype testing of the K-mirror, less than 500 μ m of alignment change was observed during a 90 degree range of stage rotation. The beam passing through the previous Dove prism wobbled about 1 mm due to its surface manufacturing limitations over the same range. When the beam wobbles during the image rotation, the pointing must be adjusted using the following mirror, requiring additional time for alignment (and is not desirable). Also the centering of the beam through the following lenses is not corrected, which introduces off-axis aberrations. For this reason, we plan to replace the Dove prisms in the two VISAR interferometer legs with K-mirrors as well.

The final two imaging lenses (L14 and L15) are placed in the system in between two fold mirrors (M9 and M17). Due to the dense configuration of optics and streak cameras on the table, the space available for the SOP after the redesign was constrained to be exactly the same as in the original design. Figure 7 compares the original and redesigned optical path in between M9 and M17 (that was indicated by the dotted red line in Figure 4).

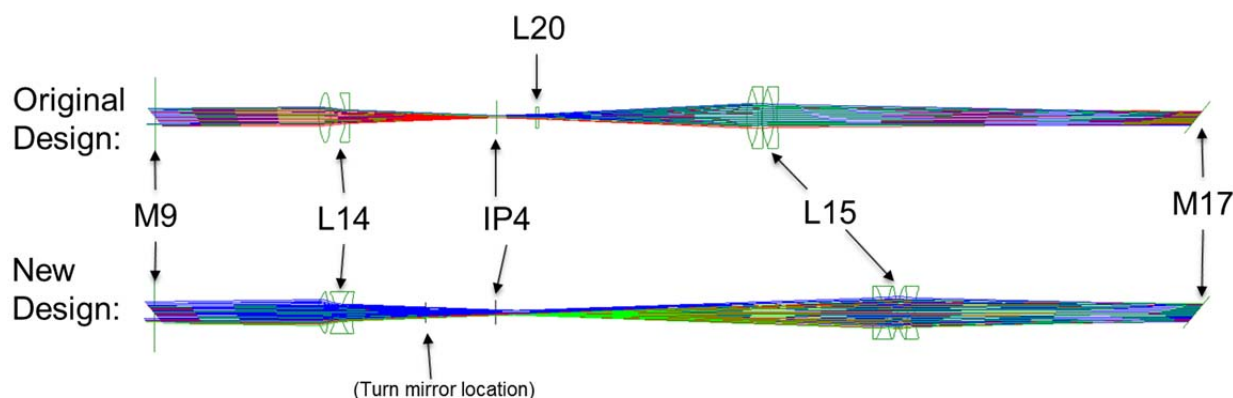


Figure 7: The optical configuration of the SOP leg between mirrors M9 and M17 before and after redesign. (IP4 is an intermediate image plane.)

The glass types used are SK5 and SF4. L14 is a triplet (SK5/air space/SF4/SK5) while L15 has five lenses (SK5/SF4/SK5/air/SK5/SF4). The lenses are cemented where not separated by air.

Figure 8 shows the Modulation Transfer Function (MTF) of the redesigned SOP optical path. The contrast exceeds the requirement of 25% at the required spatial frequency (80 line pairs/mm at the target). Further improvements to the optical design were investigated (more elements in L14 and L15), but were not pursued because the system is now limited by the spatial resolution of the streak camera.

Figure 9 shows an image captured during the commissioning of the new SOP optics. The resolution target (placed at Target Chamber Center) was illuminated with 590 nm LED light and a CCD camera (with 6.45 μ m square pixels) located at the streak camera slit plane captured the image. The line spread of the thinnest line suggests resolution is 10-15 μ m, consistent with the specification of 80 line pairs/mm at 25% contrast.

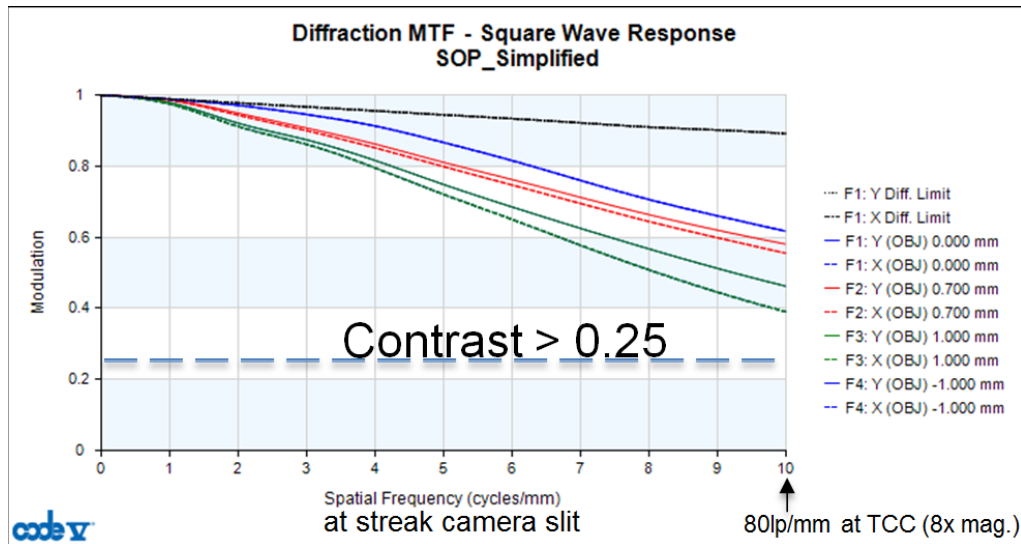


Figure 8: The MTF of the redesigned SOP optical leg exceeds the requirement of 25% contrast at 80 line pairs/mm at Target Chamber Center averaged over the 560-640nm band.

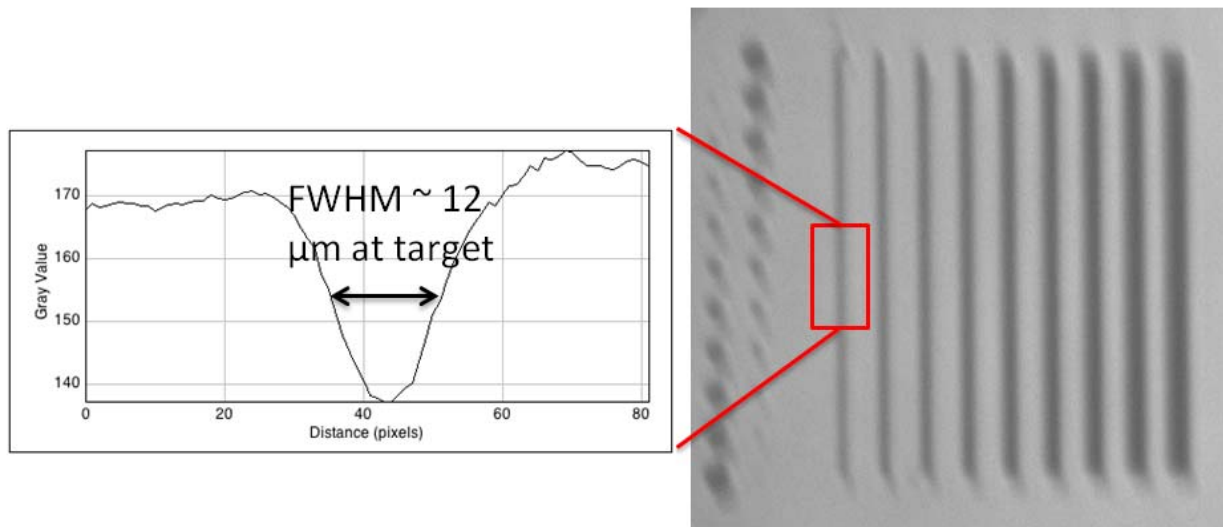


Figure 9: A dot and line resolution target image taken during commissioning of the new SOP optics. The dot diameters are 5-30 μm in diameter (increments of 2.5 μm) while the line widths are 5-25 μm (increments of 2.5 μm). There is a ghost reflection (double image) because the substrate is not AR-coated. Preliminary analysis of a lineout across the 5 μm line (Left) suggests that the spatial resolution near the center of the field of view is $\sim 12 \mu\text{m}$, almost an order of magnitude better than before the upgrade.

4. STREAK CAMERA IMPROVEMENTS

In parallel to the optical design upgrade, a gating circuit for the streak camera photocathode is being developed and tested to be implemented on the SOP. The goal is to effectively suppress the creation of photoelectrons in the streak tube on a 50ns time scale after the end of the streak sweep.⁸

5. CONCLUSIONS

The upgrades to the NIF Streaked Optical Pyrometer (SOP) include improvements both to the optical system (new imaging lenses and a K-mirror) and to the recording system (streak camera gating circuit). We look forward to collecting high quality data that is significantly more useful than previously collected on future shots and having the Streaked Optical Pyrometer become an important diagnostic on NIF. The two VISAR interferometer legs will also be upgraded to include K-mirrors and streak camera gating circuits which will further enhance the data quality.

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